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6. AUTHORS A. H. Epstein, J. H. Lang, M. A. Schmidt, S. D. Senturia, R. Ghodssi, S. Jacobson, S. Umans, P. Warren, X. Zhang, L. Frechette, S. Nagle				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Massachusetts Institute of Technology 77 Massachusetts Ave., 31-264 Cambridge, MA 02139		8. PERFORMING ORGANIZATION REPORT NUMBER		
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13. ABSTRACT (Maximum 200 words) Technology has been developed for micro electrical and mechanical systems (MEMS) micro motor-compressor and blower devices occupying less than a cubic centimeter. Made with semiconductor manufacturing techniques, these devices are intended for applications such as pressurization for fuel cells in the 50-150 watt range and the aspiration of analytical instruments. It consists of an integral silicon micro electric motor and centrifugal compressor approximately 4 mm in diameter and 2 mm thick. Technologies demonstrated include microrotors spinning at 1.5M rpm, high power density thin film electrostatic motors, and microfabricated centrifugal compressors. A complete motor-compressor device has been operated on the bench at low power only. Progress on the component technologies suggest that such a device could deliver 1-2 watts of fluid power in a 4 mm rotor size.				
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*Gas Turbine Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139*

A Final Technical Report on
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entitled

**A MICROFABRICATED MOTOR-COMPRESSOR
FOR FUEL CELL APPLICATIONS**

submitted to

US Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

ATTN: Dr. Richard Paur

AUTHORS: A. H. Epstein
J. H. Lang
M. A. Schmidt
S. D. Senturia
R. Ghodssi
S. Jacobson
S. Umans
P. Warren
X. Zhang
L. Frechette
S. Nagle

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1.0 REPORT OUTLINE

This is the final technical report on ARO Grant DAAG55-98-1-0365, entitled "A Microfabricated Motor-compressor for Fuel Cell Applications". Because the program has generated lengthy annual technical reports (including one detailing the work up to 1 month before the grant's end) and a large number of technical publications and graduate theses (which are available upon request) this final technical report is relatively brief. It consists of three sections in addition to this one: (2) a short research summary, (3) a list of participants, and (4) a list of publications and theses.

2.0 RESEARCH SUMMARY

This section summarizes the research and development status of a microfabricated silicon motor-driven compression system and its components, intended for aspiration of analytical instruments or pressurization of portable fuel cells. Recent research focused on the hydrostatic journal bearings, the electrostatic induction micromotor, and the integrated system (shown in Figure 1). The following sections will summarize the accomplishments in design, fabrication, and testing to date (detailed information can be found in Ref. [1]). Recommendations for future work will then be presented.

2.1 Component and System Design

System modeling was initially undertaken to determine the main design trade-offs and define viable configurations. Modeling of the electrostatic and fluidic forces in the micromotor identified that the viscous dissipation in the motor gap can negate the electrical torque, if the motor geometry is not designed appropriately. System modeling then allowed the exploration of

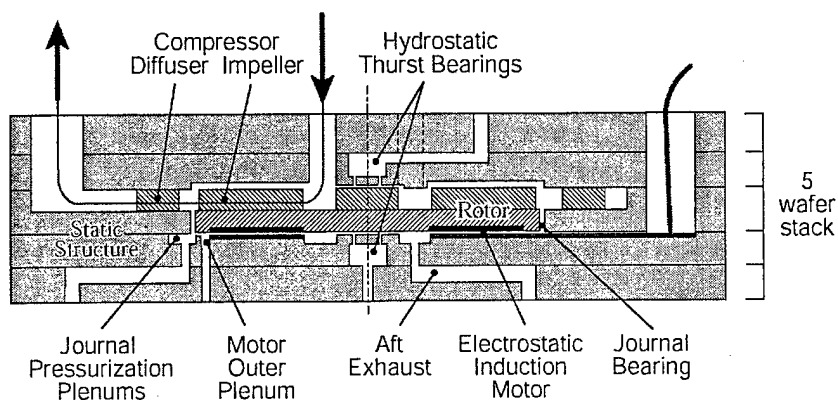


Figure 1: Cross-section schematic of the 5-wafer level motor-driven compressor.

this and other trade-offs, and the determination of viable configurations for μ Compressor (2:1 pressure ratio, 0.1 g/s of air) and μ Blower (20" H₂O pressure rise, 0.1-0.3 g/s of air) applications, with expected overall efficiencies up to 20%. The configuration of an experimental (Level 0) device to be used through this work was then defined, searching a compromise between maximum performance and reasonable challenges in fabricating and operating the first generation micromotor-driven compression system.

2.2 Microfabrication

Experimental development work was then undertaken to define a viable fabrication approach to integrate thin and thick (up to 10 microns) patterned films with deep reactive ion etched precision features in a stack of 5 fusion-bonded wafers. This led to the successful fabrication of three sets of devices: two sets of silicon-only microturbine-driven bearing rigs (no motor), and one set of micromotor-driven devices (integrating the thin and thick film motor components). This motor-driven set yielded 10 devices: 5 motor-driven compressors, 2 motor-assisted turbines, and 3 motors with no blades. The main fabrication challenges were:

- ***Wafer bonding with thin and thick films:*** overcome through a recessed design of the motor components, which includes removing the films in specified bonding areas (reducing wafer bow) and polishing the surfaces [2]. During the fabrication of this first generation of motor-driven devices, repeated chemical-mechanical polishing of the wafer surfaces was necessary in order to successfully bond the 5 wafers. This additional processing was shown to affect the motor electrical properties.
- ***Retention of the rotor during wafer processing and release:*** accomplished by a new snap-off tab approach, consisting of a mechanical link between the rotor and static structure created while bonding, which is controllably fractured to release the rotor before testing [3].
- ***Precision fabrication of the rotor and bearing components:*** accomplished through iterative development of deep reactive ion etching techniques, which resulted in geometries demonstrated to be adequate for high-speed rotation.

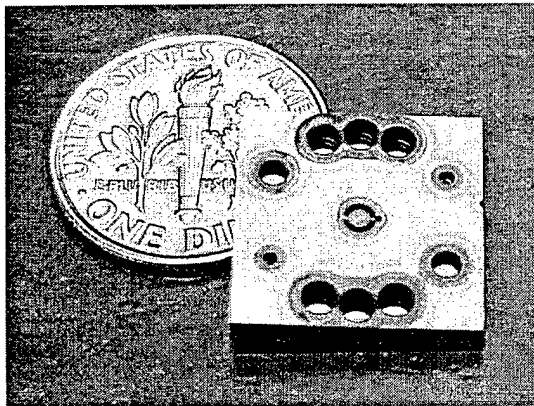
Through this effort, a viable microfabrication approach has been developed and demonstrated to build a microsystem integrating a high-voltage/high-frequency micromotor with high-speed gas-lubricated bearings and microturbomachinery. Improvements on this fabrication process are necessary in order to increase the power output and efficiency of the electrical machinery, as well as to improve the wafer-bonding yield with the presence of thin and thick films.

2.3 Experimental Development

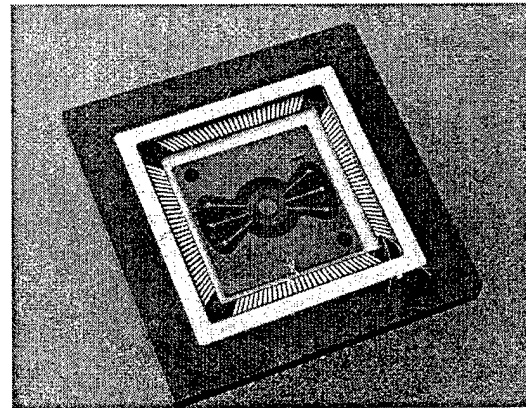
The microdevices built were used for the component development and system demonstration. In addition, macro-scale experiments provided an assessment and insight on component performance. This section will summarize the experimental development effort of the bearings, turbomachinery, electromechanics, and the integrated system. A photograph of a completed microdevice, the stator alone mounted for electrical testing, and an SEM enlargement of the stator are shown in Figure 2.

2.3.1 High-Speed Bearing Operation

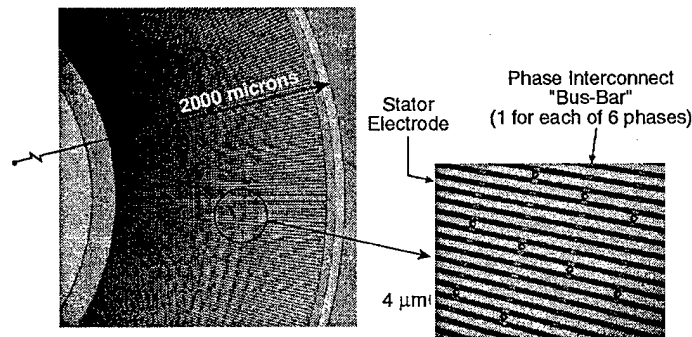
The silicon bearing rigs, driven with an air turbine, were then used to demonstrate repeatable, sustained high-speed rotation [2]. These microturbines have been spun in a stable and sustained manner up to 1.4 million rpm (300 m/s tip speed) as shown in Figure 3, which is



(a) complete motor compressor die



(b) stator mounted for electrical testing



(c) SEM of 131 pole electrostatic stator

Figure 2: Motor-compressor.

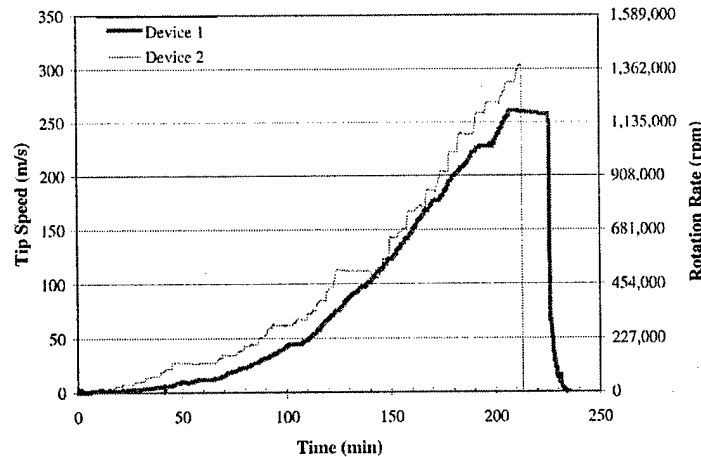


Figure 3: Speed evolution over time for two microturbine bearing rig devices.

sufficient for μ Compressor and μ Blower devices. Critical to this work was real-time monitoring of the rotordynamics and the experimental development of a pressure schedule for stable operation of the hydrostatic journal bearing, necessary for high-speed operation. This high-speed operation confirms that the microfabrication approach is sufficiently precise to provide adequately balanced rotors as fabricated. This also confirms that the single crystal silicon rotor structure can sustain the centrifugal forces up to 300 m/s tip speed.

2.3.2 *Microturbomachinery*

Turbomachinery compatible with the two-dimensional constraints of silicon etching has been designed and experimentally demonstrated. To date, the aerodynamic compressor design has not been experimentally tested at the micro-scale. However, it has been investigated numerically (2D MISES and 3D Fluent CFD codes) and experimentally using a scaled-up version of the compressor operating at matched Mach and Reynolds numbers (allowing detailed instrumentation) [4]. Results indicate that pressure ratios greater than 1.2:1 and 2:1 are achievable at tip speeds of 200 m/s and 400 m/s respectively. These measurements, taken in the macrocompressor, coincide with the numerical predictions of pressure ratio. On the other hand, measured mass flow and efficiency were lower than predicted. Overall compressor efficiency of 26% at 168 m/s and 41% at 400 m/s were measured in the macrocompressor, whereas the expected values were in the range of 50-60% [5].

In addition to the macro-scale experiments, operation of turbomachinery at the micro-scale has been demonstrated during the microturbine-driven bearing rig experiments [2]. The

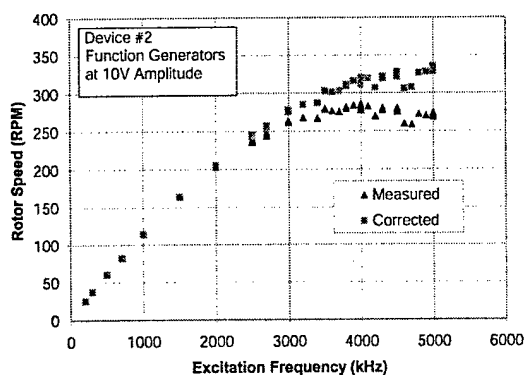
microturbine delivered a mechanical power of 5W, which is similar to the predicted results (2D MISES code).

These numerical and experimental investigations suggest that micro-scale turbomachinery can operate at the expected pressure ratios. However, further development is necessary in order to improve the efficiency. The design space for microturbomachinery has only been explored with a few aerodynamic designs. A broader, parametric investigation of the design space would allow optimized system designs, which trade pressure ratio with efficiency and flow rate to meet the requirements of specific applications. For example, low tip speed and high-pressure ratio turbomachinery would enable higher efficiency motor-driven compression systems by reducing the viscous losses in the motor gap.

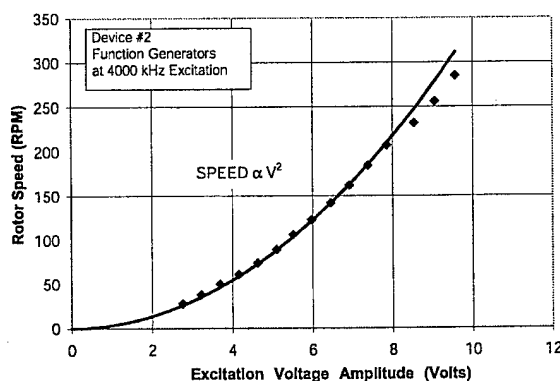
2.3.3 *Electrostatic Induction Micromotor*

The motor-driven devices from the first set were used to investigate the electrostatic induction micromotor [6] and demonstrate operation of the integrated system [1]. In addition, a tethered-micromotor was used to characterize the motor torque characteristic [7].

Low-voltage motor characterization - The motor torque curves were measured at low excitation voltage and found to exhibit typical induction machine characteristics, such as a peak in torque as a function of frequency (near 5 MHz), and a quadratic dependence on voltage (Figure 4). The peak of the torque curve was found to be at a significantly higher operating frequency than the design intent of 0.7 MHz. This was attributed to an increase in rotor film conductivity, resulting from unplanned processing during the fabrication of this first generation



(a) Effect of varying the stator frequency



(b) Effect of varying stator voltage

Figure 4: Micromotor rotation rate as a function of (a) stator excitation frequency (constant 10V amplitude), and (b) stator excitation voltage (constant 4 MHz frequency).

of devices. Furthermore, the motor gap was measured to be 4 microns, instead of the 3 microns design intent. This has the effect of lowering the predicted peak torque from $260 \mu\text{Nm/kV}^2$ to $170 \mu\text{Nm/kV}^2$. The measured peak torque was found to be more on the order of $65 \mu\text{Nm/kV}^2$, a factor of 2.7 lower than predicted. More detailed modeling of the floating potential between electrodes reduced the predicted torque, leaving a discrepancy factor of 2.1 between the predicted and measured torque per unit voltage squared. Although the viscous drag and the electrical structure have been characterized, further experimental investigation and testing of other devices is necessary in order to determine exact cause for reduced motor performance. Latest results from a tethered-motor indicate torque levels to the level ($\mu\text{Nm/kV}^2$) originally expected.

High-voltage operation - The maximum speed achieved to date by a motor-driven device is 15,000 RPM (3 m/s tip speed) at 100V amplitude and 1.8 MHz. Based on viscous drag predictions and measurements, the motor is calculated to deliver a torque of at least $0.3 \mu\text{Nm}$, corresponding to a shaft power of 0.5 mW. Operation at the peak of the torque curve (~5 MHz) was not possible with the high-voltage power electronics due to their limited frequency range (1.8 MHz). Furthermore, voltage amplitudes were limited to 100V, since electrical breakdown occurred beyond that point. Reduced voltage operation (100V instead of the 300V design intent) has the effect of reducing the torque by almost one order of magnitude.

2.3.4 System Demonstration

Integrated fabrication and simultaneous operation of the gas-lubricated bearings, turbomachinery, and micromotor were demonstrated [1]. No pressure rise was measured from the compressor, however, since the motor-driven devices operated at low tip speed (3 m/s versus the design intent of 200 m/s) due to the low motor torque. A micromotor with turbine blades has been spun up to 400,000 rpm using the turbine as a supplementary source of torque. This demonstrated high-speed operation of the integrated system and structural integrity of the composite rotor (silicon rotor with thin and thick films), at least up to those speeds. Demonstration of the micro-compression system requires proper operation of all its main components, and will only be possible once increased motor torque is achieved. Further experimental characterization of this first-of-a-kind micromotor is necessary in order to better assess and extend its performance.

2.4 Technology Assessment

Overall, the main components and the integrated system have been designed and

demonstrated at the micro-scale, but require further development to achieve the desired levels of performance:

- Hydrostatic Gas Bearings:
 - Demonstrated up to 300 m/s tip speed (1.4 Million RPM)
 - Imbalance levels acceptable as fabricated
 - Simple structure sustained centrifugal forces at 300 m/s tip speed
- 1. Micro-Turbomachinery:
 - Compressor demonstrated required pressure rise (macro-compressor)
 - Efficiency lower than expected (macro-compressor), but adequate
 - Micro-scale turbomachinery demonstrated (microturbine)
- Electrostatic Induction Micromotor
 - Demonstrated with polysilicon stator
 - Stator breakdown limits maximum speed
 - Lower torque than expected
 - Improved fabrication can increase torque
- Integrated system: 5-wafer stack with turbomachinery, motor, bearingsSystem Operation – Demonstrated
 - Microfabrication Approach – Demonstrated

Although the microfabrication technology has been developed and demonstrated, improvements are necessary, mostly in order to significantly improve the motor performance. Table 1 summarizes the problems encountered with the electrostatic motor, and the potential increase in torque and motor shaft power. Because increased torque increases the speed at which the compressor spins, the motor power produced increases faster than the torque.

Table 1: Potential Improvements in Motor Performance

Engineering Issue	Torque Increase	Power Increase
1. Proper rotor conductivity (torque peak matched to electronics frequency)	2 x	4 x
2. Breakdown voltage increase	9 x	71 x
3. Reduced motor gap	1.5 x	2.2 x
Total potential increase	27 x	620 x

First, torque can be optimized by matching the rotor conductor charge relaxation time (which sets the frequency at which the motor torque is maximum) to the capability of the power electronics. This requires extending the frequency range of the power electronics; improving the fabrication process for the rotor conductor; temperature-controlling the experiment (the rotor film conductivity is to be a function of temperature, allowing control over the peak torque frequency).

Second, preliminary testing on the platinum electrode structures shows that operation at 300V can be achieved. Experimental results indicate that the electrode material (metal or polysilicon) and processing conditions (electrode side-wall roughness and residue) are factors inducing breakdown at lower voltages and that the platinum stators are viable at the higher voltages.

The third issue listed in Table 1 requires the fabrication of a new set of devices. Adjusting the film thickness in the motor process flow can easily control the motor gap, reducing it from 4 to 3 microns. Experiments with mechanically clamped (as opposed to wafer bonded) tethered motors on platinum stators indicate that the higher torque predicted will be achieved.

2.5 Conclusions

Based on the measured torque of $65 \mu\text{Nm/kV}^2$ and the macrocompressor results, the micromotor-compressor performance can be predicted at higher voltage. Operated at peak torque operation at 300V, the current motor-compressor devices would run at 260,000 rpm, delivering 700 sccm of air at 5" H₂O. New devices with the same design (Level 0 experimental device) which met the design specifications (3 micron motor gap), would run at 370,000 rpm, delivering 1000 sccm of air at 12" H₂O. The motor would then be providing about 0.3 W of mechanical power.

With the improvements anticipated from the metal-conductor, quartz-insulator stators, these devices should be capable of reaching their design intent of 1-2 watts of mechanical power (and concomitant air pumping) in a 4 mm rotor diameter package.

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3.0 MICROENGINE PROJECT TECHNICAL PERSONNEL

Name

Primary Discipline

Faculty:

Prof. Kenneth Breuer	Fluids, Instrumentation
Prof. John Brisson	Thermal Systems, Heat Transfer
Prof. Alan H. Epstein	Engine Design, Fluids
Prof. Jeffrey H. Lang	Electromechanics
Prof. Martin A. Schmidt	μ Fab, Processes
Prof. Stephen D. Senturia	μ Fab, Processes & Materials
Prof. Mark S. Spearing	Structures, Materials
Prof. Ian A. Waitz	Combustion

Technical Staff:

Dr. G.K. Ananthasuresh (Post Doc)	μ Fab Modeling
Dr. A. Ayon (Post Doc)	μ Fab, Processes
Dr. Christopher Cadou (Post Doc)	Fluids, Combustion
Dr. Fredric F. Ehrich (Senior Lecturer)	Rotor Dynamics, Design
Eric Esteve (Visiting Eng.)	Fluids, Engines
Dr. Anthony Forte	μ Fabrication
Dr. Gautam Gauba (Post Doc)	Combustion
Dr. Reza Ghodssi	μ Fabrication
Dr. Yifang Gong (Post Doc)	Turbomachinery
Dr. Paul Holke (Post Doc)	μ Fabrication
Dr. Eugene W. Huang (LL Tech. Staff)	Structures
Dr. Stuart A. Jacobson (Engineer)	Fluids
Dr. Ravi Khanna (Research Eng.)	μ Fabrication
Dr. Carol Livermore (Post Doc)	Electromechanics
Steven Lukachko (Research Eng.)	Combustion
Dr. Paul Maki (LL Tech Staff)	μ Fabrication
Dr. James Paduano (Principal Eng.)	Controls
Larry Retherford, Jr. (LL Tech. Staff)	Packaging
Dr. Choon S. Tan (Principal Eng.)	Turbomachinery
Dr. Steven Umans	Electromechanics
Dr. Richard Walker (C.S. Draper Labs)	Gas Bearings
Paul Warren	Electronics
Dr. Wenjing Ye (Post Doc)	Structures
Patrick Yip (LL Tech Staff)	MAV Avionics
Dr. Xin Zhang (Post Doc)	μ Fabrication

Graduate Students:

Dye-Zone Chen	μ Fabrication, Instrumentation
Kuo-Shen Chen	Structures
Dongwon Choi	Structures & Materials
Luc Frechette	Turbomachinery Systems

Tod Harrison
 Kashif Khan
 Jin-Wook Lee
 Chuang-Chia Lin
 Chunmei Liu
 Kevin Lohner
 Adam London
 Amit Mehra
 Bruno Miller
 Jose Miranda
 Hyug-Soo Moon
 Steve Nagle
 D.J. Orr
 Baudoin Philippon
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 John Protz
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 Turbomachinery
 Fluids Modelling
 Engine Systems
 Bearings
 Turbomachinery
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